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Sandwich Structure - An Evolving Concept

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ABSTRACT

Sandwich construction has been used for many years in aircraft and missiles, because of its ability to provide strong, stiff, lightweight structures. While the technology is well-developed for certain combinations of materials, there are many new developments which will have a significant impact on future applications. These new developments can be grouped into the following categories:

1. Joining methods.
2. Materials.
3. Geometries.

This paper describes new technologies being developed in each of these categories and the impact they will have on sandwich construction.

Sandwich Structure - An Evolving Concept

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TO START, we will define certain terms which will be used throughout this paper. A sandwich structure, in the broadest sense, can be thought of as a laminar structure consisting of face sheets of relatively thin, strong materials separated by a low density core material. This broad definition encompasses a wide diversity of substances, including plant stems, bones, teeth, corrugated cardboard, as well as the structures produced by adhesively bonding skins to core materials to produce conventional, aerospace-type sandwich structures. There are three features which are significant with respect to sandwich structures. They are:

1. The primary load-carrying members are the face sheets stabilized by the low density core material.
2. The structure can be either orthotropic or isotropic within the plane of the sandwich, as the design indicates.
3. The structure is macroscopically nonhomogeneous.

Since this paper deals mainly with aerospace-type structures, most references to sandwich construction will deal with the low strength and density core, high strength and density skin combinations common to aerospace structures.

A second term to be used later on is "composites." A composite material can be thought of as a mixture of two or more materials, intimately combined and bound together, so that the resultant behaves more or less as a single material. Typical composite materials include wood, fiberboard, many metallic alloys, cement, and reinforced plastics. In contrast to sandwich structure, a composite material is macroscopically homogeneous, but microscopically nonhomogeneous. Obviously, composite materials can and, frequently, are used in sandwich construction.

The term "advanced composites" generally is used to describe fiber-reinforced plastics or metals where the fiber used is stiffer than ordinary glass fiber and fiber orientation is controlled so that the fiber is the main load-carrying component.

The term "composite structure" sometimes is used to de-

scribe a structure made in part or totally from composite materials. However, in some cases the term composite structure has been applied to sandwich structures, the justification being that the structure is made up of more than one substance, hence, is a composite.

Because of the generally accepted use of the terms "composite," and "advanced composite," as already defined, the term "composite structure" should be restricted to refer only to a structure made with composite materials, and should not be thought of as a sandwich structure.

It is the intent of this paper to call to your attention new developments in sandwich construction which will have a major impact on aerospace hardware, especially in the next 5-10 years. These new developments can be categorized as falling into one of three major areas as follows:

1. Joining methods.
2. Materials.
3. Geometries.

JOINING METHODS

Because of the nature of sandwich construction, its performance is intimately associated with the joining method, and lack of an acceptable and/or economically practical joining method has restricted certain materials from use in sandwich construction. In other instances, the method used to join core to face sheets has been the limiting factor in fully realizing the potential of the materials available. Consequently, considerable effort has been directed to the development of organic adhesives, braze alloys, welding and diffusion bonding techniques, and the results of these developments lead directly to a fuller and more efficient utilization of sandwich construction. Generally, a high quality joint is necessary in order to achieve the full strength of the core material.

There are two areas of new development in adhesives which

will have a significant impact on the future of sandwich construction. The first of these is in the area of high temperature systems. Organic adhesives always have been temperature limited both with respect to strength at elevated temperatures, and ability to resist oxidative degradation in heated air. At the present time, however, there are adhesive systems available which cover the full temperature range approximate to most aluminum alloys with the possible exception of very long exposure times. Some data on long time aging at various elevated temperature are presented in Figs. 1-4. While additional progress is needed in this area, it appears that solutions will be forthcoming as a natural outgrowth of current technology.

For high temperature ranges, appropriate to titanium alloys, the picture is somewhat different. The best system available are at best barely acceptable for joining titanium sandwich structures, and can be counted on for only limited service at temperatures in excess of 500 F, with relatively low strength levels (Fig. 5). However, the synthesis of a series of new polyheterocyclic polymers, including polybenzimidazole, polyimide, polyquinoxaline, and similar systems, has opened the door to a whole series of new polymers which can be used for adhesive formulation. Based on preliminary data, there is

good reason to hope that by the mid-1970's, high strength systems will be available which will be as useful on titanium as current systems are on aluminum.

For high temperature sandwich structures, brazing is the most common joining system. At Rohr Corp., we have produced over 12,000 brazed panels, using various steel alloys, during the past decade. The current production rate is about

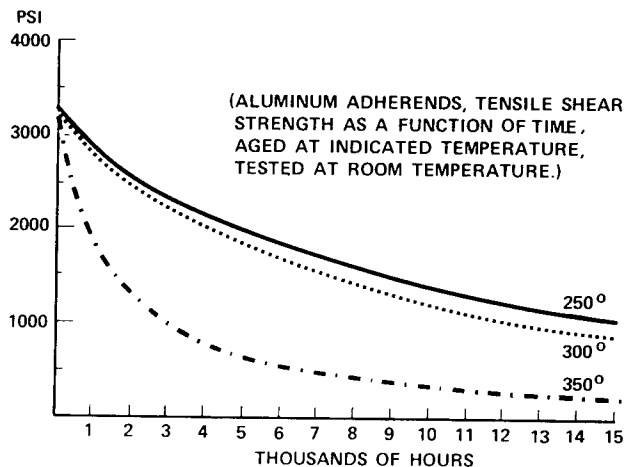


Fig. 1 - High temperature resistance of a structural adhesive (HT-424, a phenolic/epoxy)

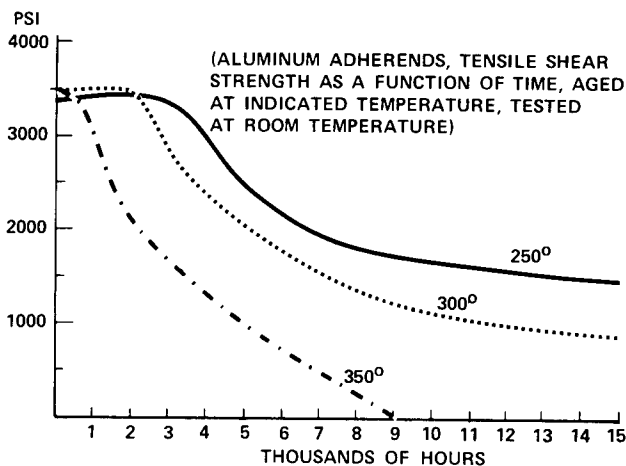


Fig. 2 - High temperature resistance of a structural adhesive (Metlbond 329, a modified epoxy)

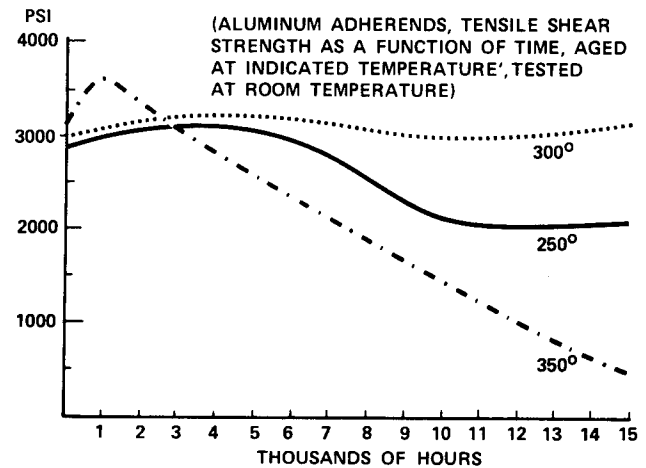


Fig. 3 - High temperature resistance of a structural adhesive (FM 96, a modified epoxy)

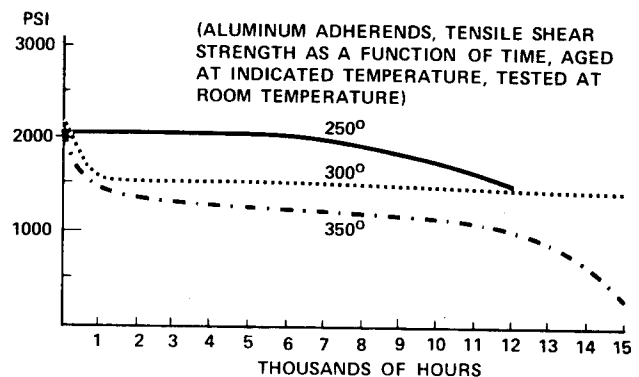


Fig. 4 - High temperature resistance of a structural adhesive (AF 131, a modified epoxy)

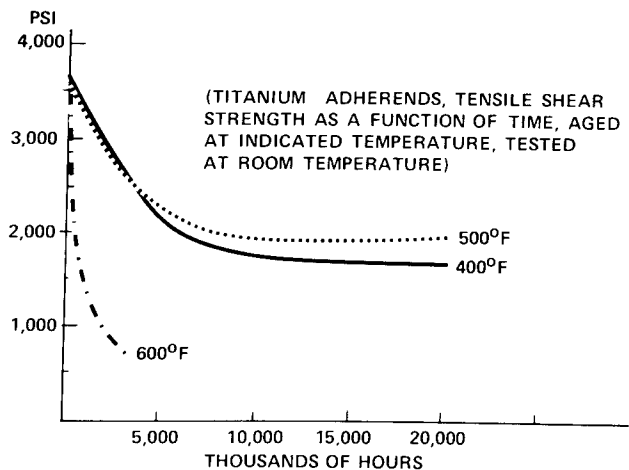


Fig. 5 - High temperature resistance of a structural adhesive (FM 34, a polyimide)

80 panels per day. While production costs usually are somewhat higher than adhesive bonded structures, and there are processing and inspection problems, these problems are yielding to continuing process development. A similar situation exists with respect to welded steel sandwich construction, and its continued development and use can be predicted.

For brazed titanium sandwich construction, however, the situation is different. Because of the chemical reactivity of titanium, especially at elevated temperature, there are severe technical problems involving interaction between the titanium and the braze alloy. The result of this interaction frequently is a brittle zone which may make the joint structurally unacceptable. However, even if a brittle joint is structurally acceptable from the standpoint of static strength levels, environmental factors such as high noise levels leading to sonic fatigue failures, or high temperatures which, in a corrosive environment may lead to stress corrosion, become significant. A second potential problem area is that of galvanic corrosion, in a moist environment, and some braze alloys are unacceptable or mar-

ginal from the corrosion standpoint. These problems are basic to the chemistry of the materials, and indirect or alternate solutions are indicated.

At the present time, there are three possible approaches under active development, namely:

1. Welding.
2. Diffusion bonding.
3. Aluminum alloy brazing.

Each process has certain good and bad features, and probably each will find its own applications as experience reveals its true potential.

One method we are especially interested in at Rohr is liquid eutectic assisted diffusion bonding. This process, which we refer to as LID (Liquid Interface Diffusion) bonding consists of locating a small amount of a reactive braze alloy on the edge of the titanium core material. This alloy is selected so that it will liquify when heated to some relatively high temperature, thus forming a bridge between core and facing sheet. Once this bridge is established, diffusion takes place which dilutes the components of the braze alloy to a concentration so low that they no longer influence the properties of the titanium. Table 1 contains some of the test data accumulated, and the photograph (Fig. 6) illustrates a typical cylindrical section made by the LID process. We believe that diffusion bonded titanium sandwich construction will become a significant structural configuration in the coming years.

Table 1 - Typical Test Data on LID Bonded Titanium Sandwich Structure

Core: 1/2 in. Cell Size, 0.003 in. Foil Ti-3DP-2.5V
Facings: 0.020 Ti-6Al-4V

Flatwise tensile, psi	2500
Flatwise compression, psi	1350
Core shear stress	
[Plate shear, rt.	
Long., psi	745
Trans., psi	565
Beam flexural	
Long., psi	750
Core shear modulus	
Long., psi	62,000
Trans., psi	36,000
Edgewise compression	
0.080 faces, psi	126,000
0.012 faces, psi	114,000

MATERIALS

By far the most exciting materials development applicable to sandwich construction is that of advanced composite materials. Because of the extent of activity in this field, it is not possible to cover, other than superficially, current activities in advanced composites. However, it is of interest to note that within the past year the prototype structures listed in Table 2 have been subjected to some form of static or dynamic test program, and in all instances failures occurred near or at the predicted load level. This performance record is a reflection of the substantial design and analysis effort, supported by extensive subscale testing, which has been a part of the overall advanced composites effort. Based on these results, and the proven structural efficiency it is apparent that from a purely technical standpoint, advanced composite sandwich structures are ready for full-scale exploitation. However, there are economic constraints associated with raw materials costs, which currently are in the range of 200-300 lb. Even more significant is the lack of well-developed manufacturing technology. Most parts are being produced under semilaboratory environments, and there is a need for more efficient manufacturing techniques, process and quality assurance specifications, and nondestructive testing procedures. While a number of companies are experimenting with automated layup machines, substantial improvements are needed in order to realize the potential of advanced composite materials.

Fig. 7 shows a prototype automated tape wrapping machine capable of producing flat or rectangular cross-section straight sections, using N/C tape control. In operation, a pres-

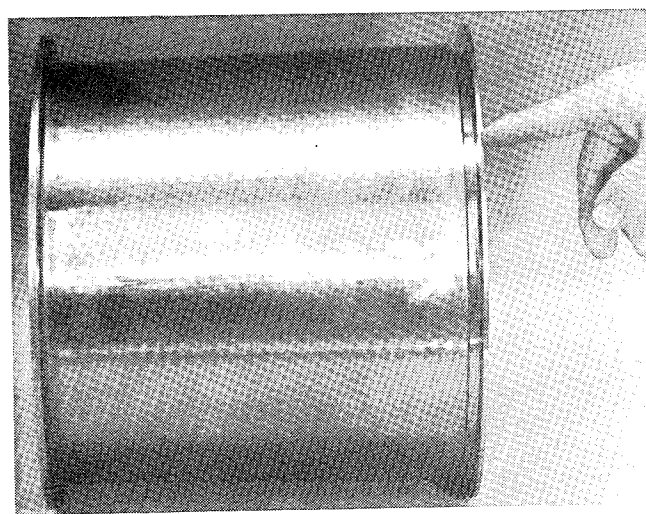


Fig. 6 - LID bonded titanium sandwich cylinder

surized roller is moved across a flat surface, and rolls on a strip of prepreg tape. The equipment is programmed to lay down a series of passes, with cutoff, repositioning, and restart capabilities built into the equipment. Using this technique, the entire layup can be automated and the result is a cost savings as well as an increase in quality, due to the tension and fiber placement control possible with equipment as compared to a hand layup procedure. It is of interest to note that automation becomes more significant as the size and mass of the part increase, and for significant sizes involving several hundred or more pounds of material, automation is almost a requirement. Considerable effort is being expended by a number of companies anticipating that automated layup techniques are going to be used in the fabrication of large advanced composite sandwich structures.

From the materials standpoint, the core material used in a typical sandwich structure can have a significant influence on overall structural efficiency. Fig. 8 shows the predicted weights of a series of equally loaded panels using various core materials. It is apparent that where weight savings are significant, core manufactured from high strength aluminum alloys

and titanium alloys are of increasing interest. Core made from these alloys is about 15 times more expensive than conventional core, since the foil must be preformed prior to the node bonding step. This is necessary because the conventional process of strip bonding sheets of foil and subsequently expanding this so-called "hobe" to the desired geometry, is not possible because the adhesive is not strong enough to deform the metal. Because of these circumstances, automated production facilities for the manufacture of high strength performed core

Table 2 - Tests Results on Advanced Composite Prototype Structures

		Percent of Ultimate
F-111 horizontal stabilizer	1st test item	91
	Redesign	100
C-5A leading edge slat	Boron/epoxy	100
	Graphite/epoxy	103
Advanced fighter wing box	Tested at 320 F	124
F-4 rudder (designed for stiffness)		250
F-14 horizontal tail		110

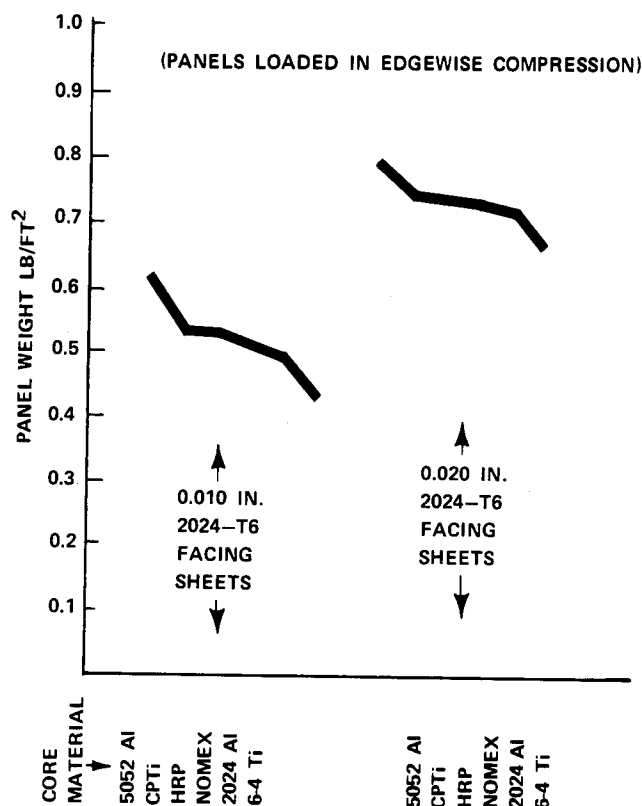


Fig. 8 - Weight-strength comparison for panels made with various core materials

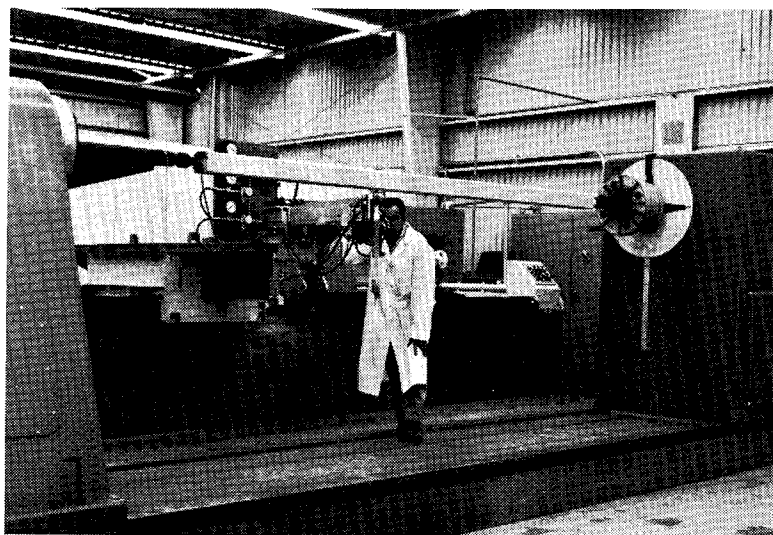


Fig. 7 - Automated tape wrapping equipment for fabrication of advanced composite structure

are needed. In addition to making high strength aluminum, titanium, and steel alloy cores available at more competitive prices, the facility should be able to produce varying density core by control of either cell size, foil thickness, or both.

In the past few years, some questions have been raised on the service life of adhesive bonded aluminum sandwich structures exposed to unusually severe conditions of moisture and salt spray in a warm climate. Under these conditions, service of some bonded structures have been shorter than anticipated, based on service in more common climatic conditions. This problem has commonly been attributed to the nature of the adhesive system used or to special processing procedures ordinarily used in the bonding process. Recently, however, it has been shown that one major cause of this problem is galvanic corrosion involving different alloys of aluminum used in the bonded assembly. The most common problem has resulted from the customary practice of using clad aluminum as a bonding surface. Since cladding on aluminum is sacrificial with respect to the base alloy, the clad layer will become anodic in a corrosive environment; hence, it will oxidize and be destroyed. This results in the destruction of the bond between adhesive and metal. In order to control this type of delamination, it is necessary to select the proper alloy combinations so that galvanic corrosion at the metal/adhesive interface does not take place. Fig. 9 shows some test panels prepared for an experimental program on corrosion control. In this test, metal laminates containing both aluminum rivets and steel bolts were exposed to salt spray and, subsequently, peeled apart to reveal the condition of the bond line. It is apparent that the bare alloy bond lines show no indication of corrosion, whereas the clad ones are seriously damaged by corrosion.

GEOMETRIES

Practically all aerospace sandwich hardware thus far has consisted of hexagonal-shaped core bonded to sheets of metal or reinforced plastics. The hexagonal cell shape has at least been determined, in part, by the method of manufacture.

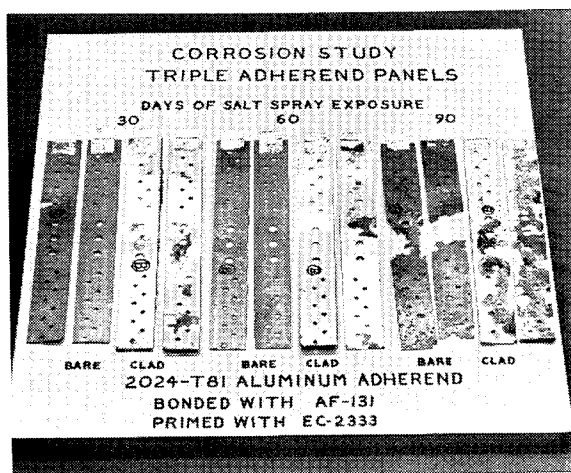


Fig. 9 - Comparison of bond line corrosion of bare and clad adhesive bonded panels subjected to salt spray exposure

Since steel core is produced by a preformed and seam-welded technique, the node bonds are relatively narrow compared to adhesive bonded core. Consequently, welded core is approximately square-cell in shape. Theoretical calculations reveal that the square-cell shape is slightly more efficient (Fig. 10), since the double foil thickness at the adhesive bonded node is redundant.

In addition to the efficiencies obtained by reducing the node bond area, there are several other geometrical factors which can lead to increased structural efficiency. First, if the foil is corrugated in a sine wave pattern prior to the core manufacturing step, increased compression and shear strength result. While this procedure gives a slight increase in core density, for a given cell size and foil thickness, the increased strength results in an overall weight savings for a given requirement as compared to flat wall core (Fig. 11). A second geometrical

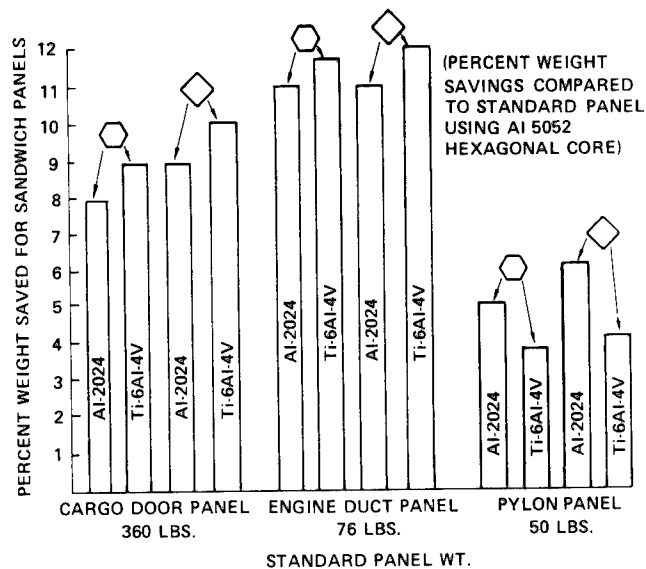


Fig. 10 - Sandwich panel weight comparisons—hexagonal versus square cell core

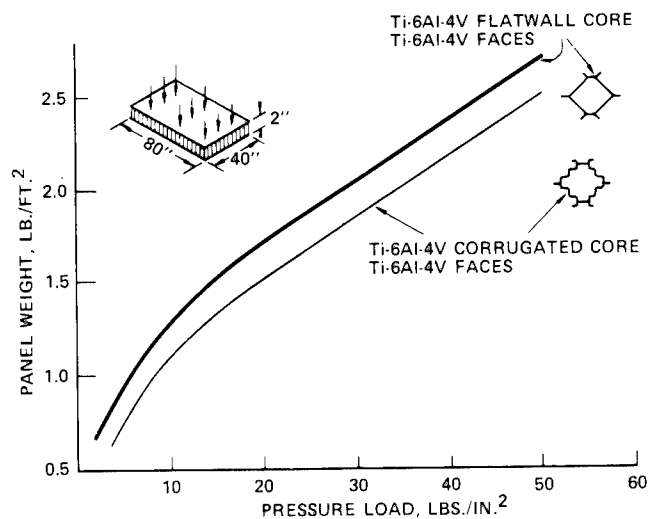


Fig. 11 - Sandwich panel weight versus load carrying capability for pressure loaded panels

variation consists in varying the density of the core to that required by the load spectrum. For a typical tapered control surface, such as a trailing edge, weight savings as shown in Fig. 12 can be expected. A third factor influencing structural efficiency consists in using multilayered sandwich configurations,

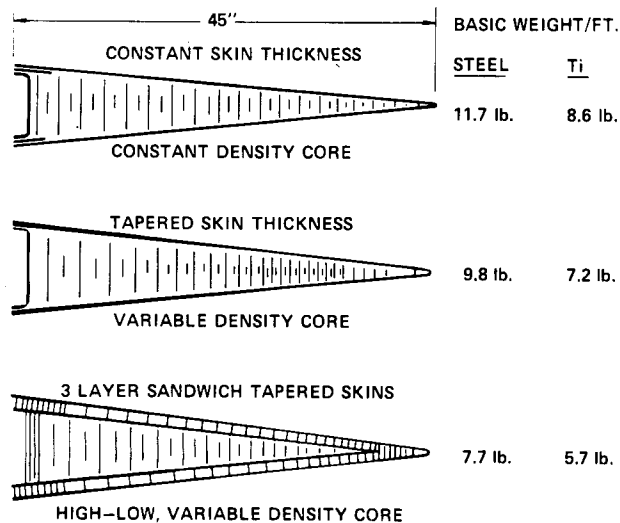


Fig. 12 - Panel weight comparisons for several geometrical configurations

also illustrated in Fig. 12. In essence, this procedure permits an additional degree of density gradation, and weight savings can be achieved as illustrated. However, it should be noted that the multilayered sandwich concept requires many bond lines, as compared to a simple configuration, and if a braze or adhesive bond is used, the weight of the joining materials may offset most or all of the other weight savings. Thus, multiple skins are most effective with diffusion bonded structures.

Another geometrical variant of interest as a compromise between structural efficiency and functionality in another role is acoustic sandwich structure. This concept, illustrated in Fig. 13, is used in certain high noise areas of jet engines in order to absorb some of the acoustic energy generated. While this type of construction is slightly less efficient, structurally, than a conventional sandwich structure, the concept is more efficient than a combination consisting of a conventional load-carrying structure plus a nonstructural acoustic absorbing linear material, in that the sound absorbing material can be integral with the primary load-carrying structure.

In conclusion, shown are some examples of new systems which will use sandwich-type construction in order to achieve an optimum utilization of materials. Both the F-14 (Fig. 14) and F-15 (Fig. 15) airplanes will make use of both aluminum and titanium sandwich construction with adhesive bonding as the joining method. Typical sandwich structures include inlet and nacelle panels. The F-111, F-4 (recent models) and F-14 all use advanced composite sandwich structures in

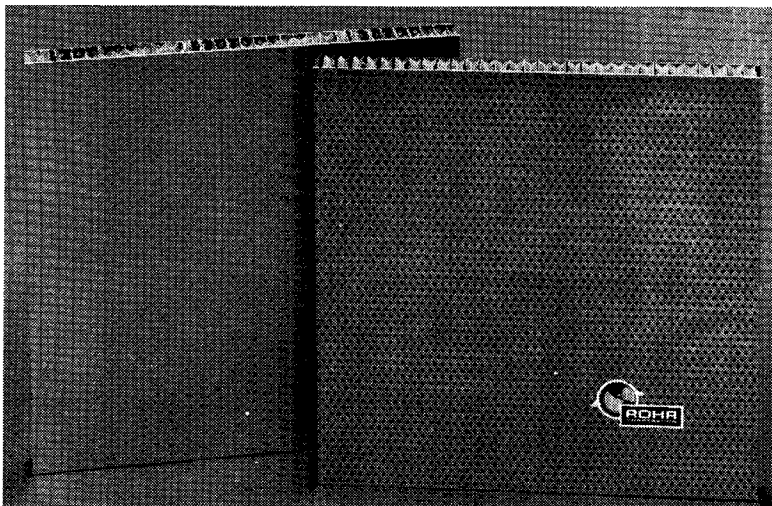


Fig. 13 - Acoustic sandwich panels

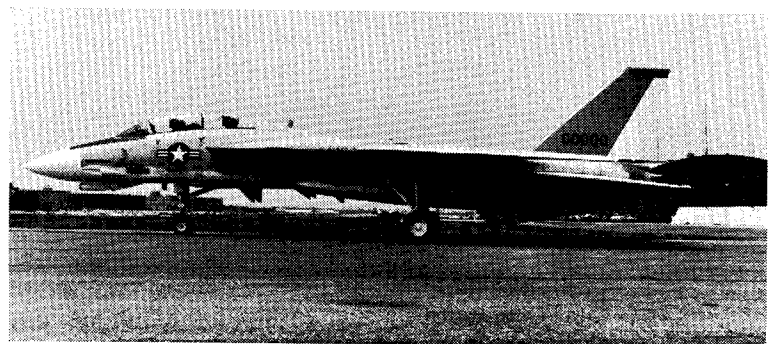


Fig. 14 - F-14 aircraft

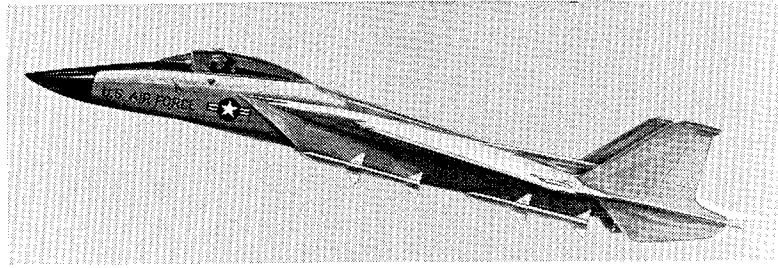


Fig. 15 - F-15 aircraft

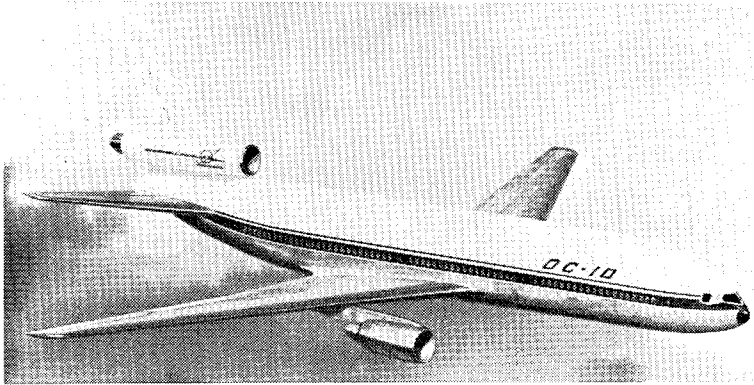


Fig. 16 - DC-10 aircraft

GEOMETRICAL FACTORS

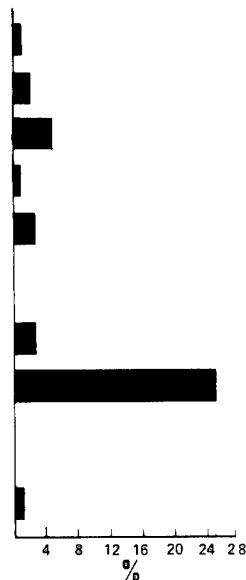
1. SQUARE CELL CORE
2. CORRUGATED FOIL CORE
3. PROGRAMMED CORE AND FACE SHEET DENSITY
4. PROGRAMMED EDGE CLOSURES
5. MULTILAYER DESIGN *

MATERIALS SELECTIONS

1. HIGH STRENGTH CORE METALS
2. ADVANCED COMPOSITES

JOINING METHODS

1. DIFFUSION BONDING



* ONLY IN CONJUNCTION WITH DIFFUSION BONDING, OTHERWISE NO WEIGHT ADVANTAGE.

Fig. 17 - Weight savings available with advanced sandwich as compared to standard honeycomb core sandwich construction

various parts of the tail assembly. The engine cases for the F-15 and B-1 probably will include all welded or diffusion bonded titanium sandwich panels. Considerable amounts of titanium sandwich structures will be used in the SST. Typical parts include certain wing panels as well as the inlet and centerbody sections. The DC-10 aircraft (Fig. 16) will use bonded acoustic panels in the inlet area, as well as sandwich construction on many other areas.

The past few years have introduced a number of new concepts in materials, joining methods, and geometries which have resulted in a significant impact on the increased use of sandwich construction in advanced aerospace systems. Fig. 17 illustrates an approximation of the magnitude of the weight savings obtainable by application of some of the concepts outlined above. While these values obviously will vary with different configurations, their relative positions are generally fixed and are indicative of the efficiencies available through application of advanced materials and design technology to advanced sandwich construction. Therefore, we can expect to see a constant increase in the use of sandwich structures with a resultant increase in operational efficiency.



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